Reprinted from Journal of Agricultural Research, 51: 191-222. August, 1935.

A PHYSIOLOGICAL STUDY OF CRACKING IN STAYMAN WINESAP APPLES

BY
LEIF VERNER

A DISSERTATION

SUBMITTED TO THE BOARD OF UNIVERSITY STUDIES OF THE JOHNS HOPKINS UNIVERSITY IN CONFORMITY WITH THE REQUIREMENT FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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A PHYSIOLOGICAL STUDY OF CRACKING IN STAYMAN WINESAP APPLES[1]

By LEIF VERNER [2]

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INTRODUCTION

Cracking of fleshy fruits while still attached to the parent plant occurs in many cultivated species. In sweet cherry, apple, plum, peach, grape, strawberry, and some citrus fruits this kind of injury is sometimes so extensive as to result in great economic loss to growers. Rapid deterioration usually follows the exposure of the ruptured tissues to the air, and the injured fruit becomes worthless of or inferior grade. Losses of this nature amounting to as much as 75 percent have been observed by the writer in commercial orchards of sweet cherries, apples, and plums. Many fruits, on the other hand—such as sour cherry and some varieties of apple—seldom exhibit this phenomenon. In many fruits there are wide varietal differences in the extent to which cracking occurs under apparently similar environmental conditions.

The present paper deals primarily with cracking of the skin and underlying tissue in the fruit of the Stayman Winesap apple. Most of the observations and experiments were made in 1932–33 at the West Virginia University Experiment Farm at Kearneysville, and in 1933–34 at the Laboratory of Plant Physiology of the Johns Hopkins University.

In this study cracking has been observed extensively in only two varieties of apples, the Stayman Winesap and the York Imperial. In the Stayman Winesap cracking occurs largely on the cheeks of the fruit in the form of irregular breaks in the skin and underlying flesh (fig. 1). Individual cracks vary from almost invisible short slits to cracks several millimeters deep that extend in an approximately horizontal plane entirely around the fruit. There is no marked predominance of cracks in any particular plane in relation to the long axis of the fruit. Late in the growing season cracks originating near the fruit stem and extending outward in nearly straight meridional lines towards the cheeks are commonly observed. Cracks around the calyx basin are rare. In the York Imperial, cracks originating

[1] Received for publication Jan. 7, 1935; issued September, 1935. Botanical contribution no. 130 from the Johns Hopkins University and scientific paper no. 143 from the West Virginia Agricultural Experiment Station. This paper was presented as a dissertation in partial fulfillment of the requirements for the degree of doctor of philosophy, received in June 1934, from the Johns Hopkins University.

[2] For many helpful suggestions relating to these experiments, especially with reference to evaporativity as a climatic feature and to water relations in general, and for much help in interpreting the results and presenting them in this form, the writer wishes to express his appreciation to Prof. Burton E. Livingston, director of the Laboratory of Plant Physiology of the Johns Hopkins University. Helpful suggestions were received also from Dr. H. E. Knowlton, head of the Horticulture Department of West Virginia University; and acknowledgment is due Dr. A. B. Groves, of the Winchester Research Laboratory, Winchester, Va., for taking the photographs used in figure 1.

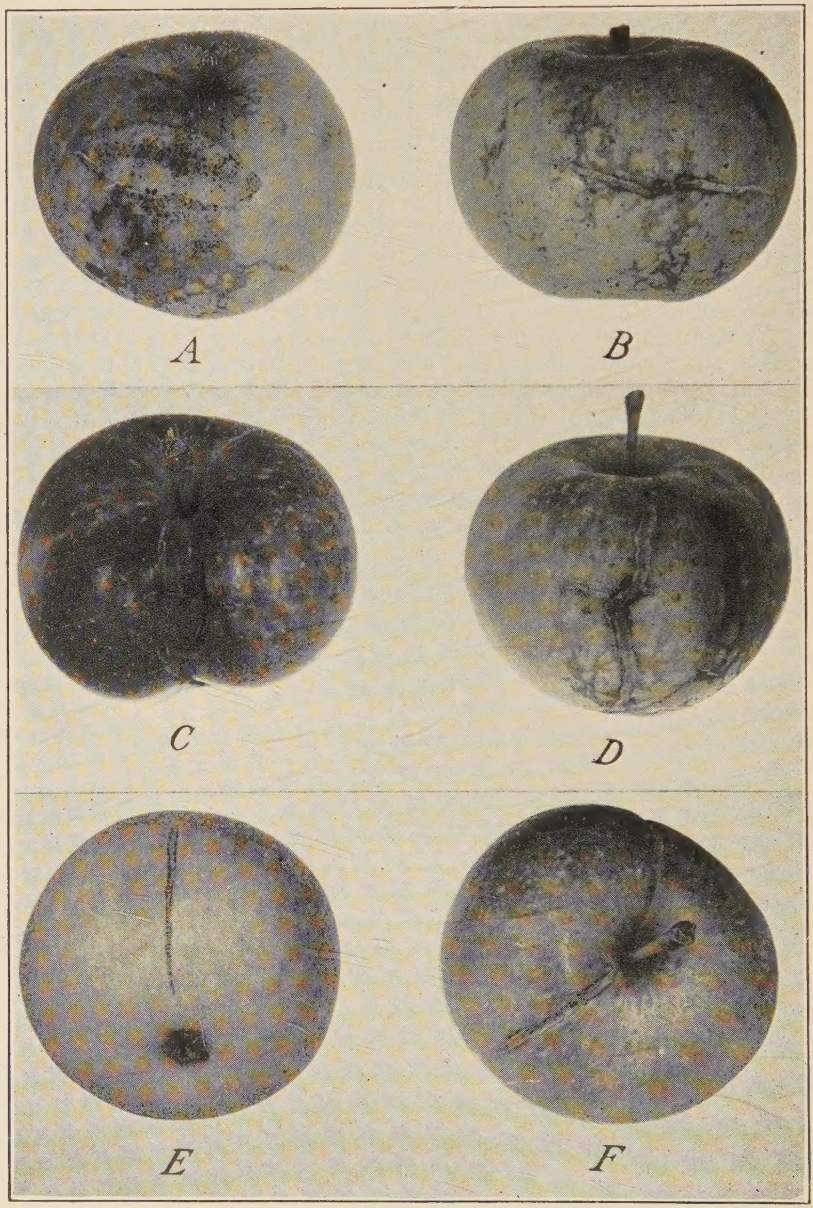

FIGURE 1.—Characteristic cracks in Stayman Winesap apples: *A*, Healed crack; *B*, *D*, and *E*, cracks originating in regions of russet; *C*, cracks originating in regions deformed by apple scab lesions; *F*, cracks originating in or near the stem depression.

at the calyx and extending like meridians toward the cheeks have been predominant in several hundred cracked specimens examined. Cracks in the stem cavity are also common in this variety, but on the cheeks of the fruit they are of much less frequent occurrence in the York Imperial than in the Stayman Winesap. In many specimens of Stayman Winesap, and in a few specimens of York Imperial, cracks that originated early in the season, when the apple was not nearly full grown, usually healed by suberization.

REVIEW OF LITERATURE

It has commonly been stated or implied that cracking of fruits is caused by a great and sudden increase in the water content of the soil, and that maintenance of a nearly constant soil-moisture content about the tree roots throughout the season of fruit growth should prevent cracking or greatly limit its severity. Discussing water relations of deciduous fruits in general, Chandler (*8, p. 165*)[3] states that "Certain injuries, such as cracking of the fruit, may result from a heavy irrigation late in its development, if growth has been checked by lack of water earlier."

Gardner, Bradford, and Hooker (*12, p. 83*) say that splitting is "most likely to occur shortly before maturity when rains follow a period of drought during which the fruit has been checked in its growth * * *. Heavy, late irrigation following a long dry season has the same effect." These writers suggest that a previous retardation of growth may render the fruit skin less able to expand rapidly in response to increased pressure within, thus predisposing the fruit to cracking when the growth rate is suddenly accelerated.

According to Heald (*17, pp. 100–101*):

> The rupturing of nearly mature, soft-skinned fruits, such as cherries, plums or tomatoes, when a rain follows a rather prolonged dry period is a fairly common phenomenon. These troubles have been proved to result from high sap pressure due to excessive water supply.

It is not clear whether the term "sap pressure" as used here refers to the vacuolar contents of the living cells in the region of the crack or to the contents of the tracheae which supply water to these cells; the causes of excessive pressure in the two cases might be very different.

Coit (*9*) discusses in some detail the development of splits in citrus fruits, with special reference to the navel orange. He says that these ruptures occur most frequently in the navel but are also found on the sides of the fruit, where they are associated with teratological cavities or "seams" in the skin. Regarding the causes of splitting in oranges, Coit states (*9, p. 328*):

> The most common theory in regard to the cause of splits is that an irregular water supply causing wide variations in the moisture content of the soil, produces a greater fluctuation in the growth of the interior than in the skin of the orange. Such a theory is quite reasonable, but such a cause should be regarded as contributory only, inasmuch as only a part of the fruit on any given tree will split.

Fawcett and Lee (*11*) point out that splits in citrus fruits are commonly associated with diseased tissues, such as lesions due to *Alternaria citri* or those accompanying the disease exanthema. In that disease the region of the oil vesicles in the rind is impregnated with gummy substances of the nature of pentosans, which, as these writers

[3] Reference is made by number (italic) to Literature Cited, p. 220.

suggest, may absorb water excessively when the water supply is plentiful and so cause rupture through abnormal swelling.

Boussingault in 1873 (*2*) demonstrated the ability of fruits of cherry, plum, pear, grape, and other horticultural forms to absorb water through the skin when submerged for a long period. Hartman and Bullis (*16*) reported that cracking of sweet cherries occurred in the Willamette Valley, Oreg., as a result of excessive water absorption by the fruit, either directly through the skin in wet weather or by way of the root system and vessels.

In extensive experiments with different periods and amounts of irrigation, Verner and Blodgett (*29*) were unable to observe any relationship between soil moisture and cracking in the three varieties of sweet cherries with which they experimented, although they tested extremes of soil moisture far beyond those usually found in irrigated orchards. Sawada (*21*), who experimented in Japan on the splitting of sweet cherries, likewise concluded that extremes of soil moisture played no direct part in producing the injury. He flooded the soil about the root system of a potted tree bearing mature fruit, but this drastic treatment failed to produce cracking.

Sawada was able to prevent cracking of sweet cherries on the tree by enclosing fruits in paraffined paper. By excluding rain by means of waterproof tarpaulins, Verner and Blodgett (*29*) succeeded in preventing the cracking of ripening fruit on large branches of sweet cherry trees in rainy periods, when severe cracking occurred on the exposed parts of the same trees. They concluded that cracking in this fruit was due mainly to direct absorption of rain water through the fruit skin. When fruits were held for a time under water, high rates of water absorption and pronounced cracking were both found to be concomitant with high concentrations of solutes in the expressed fruit juice, this concentration being regarded as a rough measure of the osmotic value of the cell sap.

Howard [4] states that he has observed splitting of sweet cherries in orchards at Mountain View, Calif., near San Francisco Bay, in periods of heavy fog without rain and without change in soil-moisture content through irrigation, and he suggests that this phenomenon may have been due to a sudden increase in the rate of water supply to the fruits, which might result from a decrease in the rate of water loss from the leaves. He says that root pressure might, under such circumstances, promote cracking by causing water to be forced into the fruit tissues from the vessels. Rixford (*20*) states that figs have been observed to split under conditions of high atmospheric humidity without rain or irrigation.

In the varieties of apples known as Cox Orange and Dunn, Campbell (*7*) and Goodwin (*13*) describe a russeting and cracking that led to great losses in the Nelson district of New Zealand. The latter writer, who describes the skin breaks of these apples as occurring only in conjunction with russeting or with lesions produced by the conothecium disease, considers the disorder as dependent upon general debility of the tree.

Sorauer (*23*) discusses the rupture of fleshy plant parts in general, considering the causal relations to be much alike in the many different forms of this disorder that he mentions, including fruit cracking in

[4] Howard, W. L. Correspondence. 1932.

cherry, plum, and grape, bursting of carrots and beets, and splitting of stems in kohlrabi, rape, bean, and potato. He says (*23, p. 322*): "All these phenomena have one characteristic in common—that they are initiated only when, after a considerable period of normal development, or still more after a previous dry period, an unusual supply of water is given suddenly."

According to Graebner (*14*), periods of drought result in the development of strengthening tissues, which usually appear first in the xylem and phloem. Mechanically strengthened cells have, as a rule, lost their ability to divide and most of their capacity to enlarge. If the water supply is greatly increased after a dry period, in the course of which the growth ability of some cells has been lost or has been greatly reduced, then the meristematic groups quickly resume growth, but corresponding growth cannot occur in the strengthened cells. Resultant differences in growth rates between contiguous mechanical and meristematic tissues may thus lead to excessive tensions, and rending of the mechanical tissue may ensue.

In a recent study by Frazier [5] it was found that tomatoes cracked most severely after heavy irrigation at the end of a prolonged dry period. Cracking was less severe in plots with frequent irrigation, which prevented excessive drying of the soil, and it was least severe in plots where the soil-moisture content remained low throughout the growing season. Shaded fruits cracked much less than those exposed to the sun.

Tracy (*25*) states that cracking of tomatoes may be prevented by enclosing the fruits when half grown in paper bags; but he points out that this treatment slightly impairs the flavor of the ripe fruit.

METHODS OF EXPERIMENTATION

The conditions that were studied in relation to cracking of apples may be divided into (1) external and (2) internal. The external conditions included those of weather (air temperature, air humidity, precipitation, evaporativity) and those of the soil, especially soil-moisture content. The internal conditions included rate of fruit enlargement, abnormalities of the peripheral region of the fruit, and freezing-point depression of the cortical tissue.

WEATHER DATA

Continuous records of temperature and relative humidity of the air were obtained throughout the growing season by means of a hygrothermograph installed in a standard United States Weather Bureau shelter located about 400 feet from the experimental block of trees. Temperatures and percentages of relative humidity, read directly from the automatic records at 2-hour intervals, were tabulated and employed as basic data. Temperature readings were used without modification, but corresponding readings of relative humidity and temperature were combined to give values of the vapor-pressure deficit.

Direct indices of the evaporating power of the air and of total sunshine intensity were obtained by means of Livingston porous porcelain atmometers (*18, 19*), both white and black spheres being used. The black sphere was of the new type, made of black porous porcelain.

[5] FRAZIER, W. A. A STUDY OF SOME FACTORS ASSOCIATED WITH THE OCCURRENCE OF CRACKS IN THE TOMATO FRUIT, 1933. (Ph. D. diss. Univ. Md.)

For 5 weeks in 1933, when the apples were thought most likely to crack, the black sphere was mounted on one end of an upright U tube of small bore (4 mm), the other end of which was joined to a vertical glass cylinder 3 cm in diameter and 24 cm high, open at the top, which served as a reservoir for supplying the atmometer with distilled water. Within this cylinder was a light, cylindrical glass float filled with air and sealed. To this float was attached a small vertical wire bearing a pen so adjusted that, as the float gradually descended in response to withdrawal of water from the reservoir, a continuous record was traced on a paper sheet borne by an upright, clock-driven drum. The slope of the tracing was thus a measure of the rate at which water evaporated from the standard black sphere.

Depth of rainfall, measured by a standard United States Weather Bureau rain gage, was recorded at intervals not exceeding 24 hours.

PROTECTION OF FRUIT FROM WETTING BY RAIN

Because water absorption through the fruit skin in periods when the latter is covered with a film of liquid water—as during and following times of precipitation—might conceivably be among the conditions that lead to cracking, some apples were covered to protect them from wetting by rain. This was accomplished by spraying with mineral oil emulsions or fish-oil soap, by enclosing apples in paper or cellophane bags, and by covering large branches of apples with waterproof tarpaulins in times of rain.

SOIL TREATMENT AND MEASUREMENT OF SOIL MOISTURE

The soil in the experimental block of trees is a clay loam of good fertility belonging to the Hagerstown series (*5*). Throughout the periods of observation on cracking there was always a moderately good stand of volunteer growth of weeds and grasses, which was undisturbed at these times.

In a region like West Virginia, which is subject to frequent and sometimes heavy summer rains, the experimental establishment of very marked differences in soil-moisture conditions in the field is very difficult, but an attempt was made to establish and maintain such soil-moisture differences among the experimental trees as were feasible. Throughout the periods when the likelihood of cracking was greatest, these differences were about as large as are ever found in orchards of this region. Special treatments with regard to soil moisture were as follows: (1) In 1933 the root system of one tree was deprived of the benefits of rains by diverting rain water from the root zone by means of waterproof tarpaulins supported on a wooden framework so arranged as to cover the soil area within and slightly beyond the spread of the branches, the intercepted water being discharged outside of that area. A marginal trench about 12 inches back from the outer edge of the tarpaulin covering served to prevent water seepage into the covered area. This trench was about 30 inches deep, extending at least 12 inches below the lowest roots intercepted, which were all cut. On October 6, when the fruit was nearly mature and when the moisture content of the upper 12 inches of soil under the tarpaulins had been reduced nearly to the wilting point, a flood irrigation equivalent to 4 inches of rainfall was given. (2) Early in the summer of 1933 several trees were mulched with

straw, the mulched area being somewhat broader than the spread of the branches. The covering, which was 4 to 6 inches deep after settling, was calculated to greatly retard water loss.

Soil samples were taken in 1933 at intervals of from 2 to 4 days between August 12 and October 7, embracing a period well in advance of, and including, that in which the most severe cracking is usually observed. At each time of sampling a cylinder of soil was taken, by means of a California soil tube (*27*), from the upper 6 inches and from the second 6 inches of soil. Samples were secured from three or more locations among the experimental trees, and the moisture percentages, calculated on the dry-weight basis, were averaged to give a single reading, which is taken to represent the soil of the experimental block as a whole.

FREEZING-POINT DETERMINATIONS

Freezing-point depressions of samples of apple tissue were ascertained from time to time by means of a Beckmann thermometer, a special tissue-cup method described by Verner (*28*) being used.

FRUITS UNDER WATER

Direct absorption of water through the fruit skin was studied for detached apples by sealing each stem and calyx opening with paraffin, weighing the fruits thus sealed, and then reweighing them after they had been kept under tap water for a time. Branches with fruits still attached were bent down and held with the fruit under water in 50-gallon barrels. By means of a steel tape graduated in millimeters the largest horizontal circumference of each apple was measured before and after this water treatment, and these measurements were compared with corresponding measurements of untreated fruits on adjacent branches.

RESULTS AND DISCUSSION

GENERAL OBSERVATIONS

Variability in Extent of Cracking

Field observations on apples have revealed marked differences in the incidence of cracking in the same orchard in different seasons, in different orchards in the same season, and in the same season among individual trees of the same orchard and branches of the same tree. For York Imperial and Stayman Winesap the extent of cracking in different orchards varied in 1932 from less than 5 to over 60 percent. At the experimental orchard near Kearneysville the percentage of fruit that cracked per Stayman Winesap tree varied from 33 to 65, the extremes appearing in adjacent trees. Two different branches of the same Stayman Winesap tree showed, respectively, 31 and 70 percent of cracking. In several cases one fruit of a spur was badly cracked while a second fruit of the same spur, with almost the same exposure and with the same outward appearance, was unaffected. Thus, while weather conditions exert a major influence in the cracking of apples, it is apparent that physiological conditions within the tree or fruit, not directly related to current weather features, are also influential.

Nature and Rate of Crack Formation

In periods when weather conditions were such as to warrant the prediction that cracking would soon occur, many fruits were examined with a hand lens at frequent intervals, and it was thus possible to detect incipient cracks when they were much less than a millimeter long and to observe the regions in which they occurred and the manner in which they enlarged and multiplied. It was evident that cracks generally appeared first in restricted areas, especially in areas of russeting, sunburn, or high skin coloration. It appeared as though the peripheral tissues were exceptionally weak in such regions or the tissue strains were more pronounced there than elsewhere. Localization was usually very definite, and it was often possible to detect a dozen or more minute breaks within an area of a square inch. Enlargement of cracks sometimes continued for several days, especially if evaporation rates were low.

Many incipient cracks apparently originated at hypertrophied lenticels of the cracking area (fig. 2). If the cracks remained small until after the weather became drier, cork was formed in the minute fissures and a russeted area might thus result. The russeting here considered may therefore have resulted, at least in part, from lenticel hypertrophy, incipient cracking, and subsequent cork formation.

Several writers have concluded that lenticel hypertrophy may be caused or promoted by greatly retarded transpiration from the plant, accompanied by a plentiful water supply to the regions of hypertrophy. Thus the formation of the corky or mealy excrescences that mark lenticel hypertrophy on young stems and branches of such trees as cherry and elder are attributed by Sorauer (*23*) to temporary retardation of foliar transpiration in periods of high atmospheric humidity. Schilberszky (*22*) concluded that hypertrophy of lenticels in apple fruits is related to an excessive water supply in the soil. Devaux (*10*) considered lenticel formation to be intimately connected with excessive moisture supply in underlying tissues, and Swingle (*24*) found that lenticel hypertrophy in stem cuttings of willow was directly correlated with their water supply under conditions of negligible evaporation. The proliferation that constitutes lenticel hypertrophy may decrease the extensibility of the neighboring peripheral cell layers and lower their mechanical resistance to being torn apart; and if that be true lenticels might be expected to mark the weakest points, at which rupture should begin whenever peripheral tissue strains become sufficiently excessive.

As to the formation of large cracks, numerous observations showed that it usually required at least several hours for these to develop. Thus, in one instance, the development of a crack 11 mm in length and about 1 mm in maximal depth required 3 hours, counting from its first clearly visible appearance as a mere slit about a millimeter long. Some cracks developed more rapidly; one attained a length of about 60 mm in 6 hours after its inception. A representative sample of the larger cracks showed successive lengths of 11, 18, 22, and 43 mm at 48-hour intervals.

RELATION OF NATURAL ENVIRONMENTAL CONDITIONS TO CRACKING

EXPLANATION OF GRAPHS

Data on natural fluctuations in soil-moisture content, rainfall, atmometric evaporation, and air humidity in relation to cracking of apples on the experimental trees in 1933 are summarized in figure 3.

FIGURE 2.—Hypertrophied lenticels, cracks, and russet development in a Stayman Winesap apple. × 3.

The smallest subdivision on the abscissa represents a 2-hour interval. The 5-week period considered (Sept. 3 to Oct. 8) covers the latter part of the period of fruit enlargement. The ordinate scale represents the index values of the respective environmental features.

The two upper graphs present the general march of soil-moisture percentage on the dry-weight basis. In the arbitrary scale of ordinates at the left, unity represents a moisture percentage of 4, which is the scale factor for these two soil-moisture graphs.

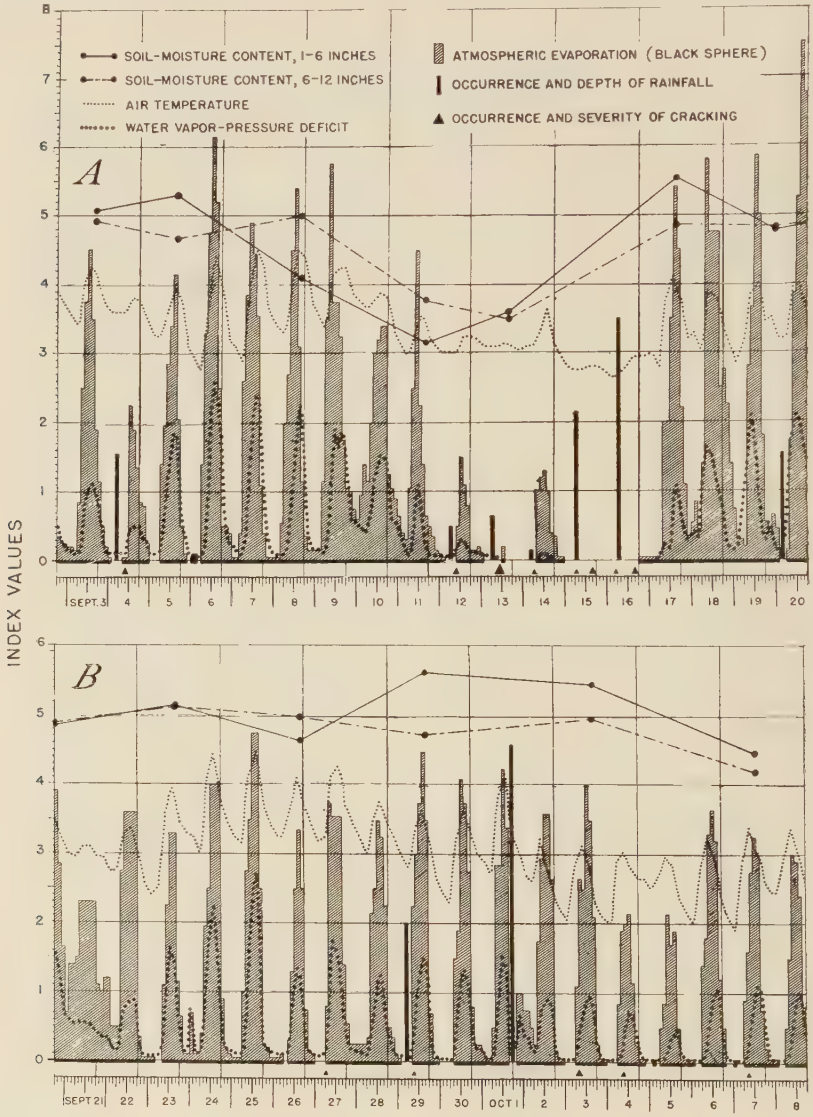
SOIL-MOISTURE CONTENT, 1-6 INCHES
SOIL-MOISTURE CONTENT, 6-12 INCHES
AIR TEMPERATURE
WATER VAPOR-PRESSURE DEFICIT
ATMOSPHERIC EVAPORATION (BLACK SPHERE)
OCCURRENCE AND DEPTH OF RAINFALL
OCCURRENCE AND SEVERITY OF CRACKING
A
B
INDEX VALUES
SEPT. 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
SEPT 21 22 23 24 25 26 27 28 29 30 OCT 1 2 3 4 5 6 7 8

FIGURE 3.—Relation of cracking in Stayman Winesap apples to fluctuations in environmental conditions Sept. 3 to Oct. 8, 1933. See text for complete explanation.

The march of air temperature is shown by the narrow dotted line, which is derived from the automatic tracing of the thermograph. The scale factor for air temperature is 20; that is, unity on the general ordinate scale at the left represents 20° F.

The wider dotted line shows the march of the water-saturation deficit of the air. This deficit is taken to represent the current evaporating power of the air with the wind and radiation factors removed. For this feature unity on the ordinate scale corresponds to a water-vapor pressure deficit of 8 mm of a barometric mercury column.

The occurrence of measurable rainfall is indicated by vertical black bars. The height of any bar shows the total depth of rain accumulated in the 24-hour period ending at 6 p. m. on the day referred to. Duration of rainfall was not recorded; therefore only a single bar is shown for each day with measurable precipitation, and all these bars have the same width, which is arbitrary. The scale factor for rainfall is 0.2 inch or approximately 0.5 cm.

Fluctuations in the rate of evaporation from the standardized black porous-porcelain atmometer sphere, exposed in the open, are shown by the hachured stepgraph of figure 3. This graph is plotted for every 2-hour period, as though it consisted of vertical bars, each 2 hours in width. The height of each bar or step represents the total accumulated water loss for its period. The scale factor for evaporation is 2 ml per 2-hour period; that is, unity on the general ordinate scale corresponds to water loss from the instrument at a mean rate of 1 ml per hour for the corresponding 2-hour period. It is at once obvious that the intensity of this feature fluctuated greatly and that there were occasional periods without measurable evaporation. For such periods this graph naturally coincides with the base line. The horizontal extent of each hachured block has been indicated by broadening the base line, and intervals without measurable water loss from the atmometer are clearly shown by the absence of the broad base line. Periods without evaporation, or periods of very slow evaporation, are of special interest, as will later appear.

Observations on cracking of the fruit were made at intervals of 2 or 3 hours in the daytime, but no observations of this sort were made at night. For each observation cracking was recorded only for the number of fruits that had been noted as uncracked at the last preceding observation. Consequently the total number of observed fruits used as a basis for these percentages became smaller as the season advanced. Naturally, the most susceptible fruits were the first to crack when external conditions favored this injury, and later observations on occurrence and degree of cracking were confined to fruits that had not already been recorded as cracked. In the present connection all cracks were considered as equal, and no attention is here given to additional cracking of fruit previously recorded as showing cracks.

Because of these considerations the percentage values derived from the observational counts should be adequately weighted or re-evaluated before being employed quantitatively in this part of the study, but no satisfactory way of so modifying them has been found. Therefore the cracking record presented in figure 3 is in very general terms as (1) slight, (2) moderate, and (3) severe; representing, respectively, about the following values: (1) from 1 to 5 percent, (2) from 6 to 15 percent, and (3) more than 15 percent. These three relative degrees of cracking are indicated, respectively, by small, medium-sized, and large black triangles placed just beneath the base line; the abscissal position of each triangle shows when the corresponding outbreak of cracking was observed.

Relation of Air Temperature and Soil Moisture to Cracking

There appears to be no correlation at all between air-temperature fluctuation and the occurrence of cracking, so far as may be judged by a study of the graphs of figure 3.

The fluctuations of soil-moisture content shown in figure 3 exhibit no relation to cracking. These fluctuations were relatively slight, and it is safe to suppose that the soil-moisture content of the first 6-inch and the second 6-inch depth was, in the 5-week period considered, never low enough to approach closely the value of the wilting coefficient of this soil. The wilting coefficient of the soil of the experiment orchard at Kearneysville may be estimated as about 10 percent on the gravimetric basis and according to Veihmeyer's (*26*) interpretation of this apparently critical value. The depth to which the present records refer (0 to 12 inches) is estimated to have included the region occupied by more than three-fifths of the roots of these trees.

Veihmeyer has shown (*26*) that the rate of water utilization by prune and peach trees with which he experimented in southern California was independent of the amount of moisture present in the soil as long as this amount was above the wilting coefficient. He found that the rate at which water was removed from the soil by a tree appeared to be determined primarily by the evaporating power of the air and the magnitude of the total leaf surface of the tree. If this is generally true of fruit trees it is hardly to be expected that changes in soil moisture within the limits usually met with in nonirrigated orchards—that is, above the wilting point and below field saturation—should affect changes in the water balance of the tree sufficient to produce cracking.

Relation of Rainfall to Cracking

Since soil-moisture content shows no apparent relation to cracking, wetting of the soil by rain is not to be regarded as among the influences that promoted this injury. If the occurrence of rain really promoted cracking in this 5-week period its influence must have been exerted in some other manner than through an increase in the supply of water to the tree roots. During rainy periods the foliage and the apples themselves were, of course, more or less completely covered with water, and it is conceivable that direct absorption of water through leaf epidermis and fruit skin may have been directly or indirectly influential in promoting the tissue strains that lead to cracking.

An indirect way in which the occurrence of a rainy period following a drier one might promote cracking is through sudden lowering of the transpiration rate, for transpiration must be practically prevented as long as the transpiring surfaces are covered with water. But in periods of little or no evaporation, transpiration must be very slow whether or not rain occurs.

However these interdependent variables, rain and evaporativity, may operate in general, a study of the graphs in figure 3 makes it clear that, although the outbreaks of cracking usually were preceded immediately by rain, this was not always so. Thus in several instances (on Sept. 27 and Oct. 3, 4, and 7) cracking was observed when there had been no recorded rain for from 36 hours to several days, and in other instances (Sept. 20 and Oct. 1) cracking failed to occur in spite of heavy rains.

Relation of Atmometric Evaporation to Cracking

Figure 3 shows, for the 5-week period represented, a very clear and consistent relation between occurrence of cracking and occurrence of very low rates of evaporation from the black atmometer sphere. Cracking was never observed except after a period of slow evaporation, and nearly every period of 6 hours or more without recorded evaporation was accompanied or immediately followed by cracking. On October 7 cracking followed two 4-hour periods without evaporation, the two periods being separated by a 2-hour interval with very low rate. On the other days when cracking occurred it was preceded in every instance by at least 6 hours without measurable water loss from the atmometer. As has been mentioned, although prolonged periods without atmometric evaporation were, in a number of instances, concomitant with periods of rainfall, there were also periods of cracking that obviously were not related at all to the occurrence of rain. Examination of figure 3 shows that these periods of cracking without antecedent rain (Sept. 27 and Oct. 3, 4, and 7) in every case were immediately preceded by from 6 to 8 hours of little or no measurable atmometric evaporation. Conversely, as has just been pointed out, on October 1 no cracking was observed during or following a rain of 0.92 inch, when the evaporation rate was zero for only 4 hours, then rose abruptly; nor was there any cracking following the lighter rain of September 20, when, also, the period of slow evaporation was short. The nonoccurrence of cracking in the prolonged periods of low evaporation on September 5 and September 30 may, perhaps, be accounted for partially or wholly by the fact that in each case there had been considerable cracking on the preceding day; presumably the apples currently most susceptible to this injury had already cracked.

Relation of Water Vapor-Pressure Deficit of the Air to Cracking

As would be expected, the graphs of vapor-pressure deficit have almost exactly the same form as the corresponding ones of atmometric evaporation. The period from September 13 to 16 (fig. 3) includes two intervals for which this deficit has zero value and both of these are without measurable atmometric evaporation. Also, both show records of severe cracking. The remaining intervals without measurable evaporation from the black sphere, as these are represented in figure 3, show very low deficit values of 1 mm or less. All the outbreaks of cracking recorded in this figure were preceded by 4 or more hours with vapor-pressure deficit below 1.6 mm.

A fairly close relationship was found to exist between relative humidity, or relative-humidity deficit, and cracking. The most extensive cracking in any 24-hour period in 1933 took place on August 24 in a 10-hour period when relative humidity was recorded as 100 percent. This period followed a rainfall of 4.25 inches. In 1932 approximately 40 percent of the crop of Stayman Winesap apples in the experimental orchard were damaged by cracking in a 38-hour period on October 17 and 18, when the recorded relative humidity at no time was below 99 percent. The total rainfall for these 2 days was 2.07 inches, but the soil had a high water content before the rain began. A heavier rain on October 5 and 6, totaling 2.85 inches

but accompanied by humidity for the most part well below 90 percent, caused no cracking. Similar instances of apparent association of cracking with prolonged high air humidity, either with or without rainfall, were observed many times in 1932 and 1933 and in several varieties of apples, including Stayman Winesap, York Imperial, Northern Spy, Wealthy, and Yellow Transparent. At no time during these 2 years was cracking observed except during periods of 8 hours or more when relative humidity was above 90 percent.

ORCHARD EXPERIMENTS WITH MODIFICATION OF NATURAL ENVIRONMENTAL CONDITIONS

Modification of Soil-Moisture Content

In an attempt to obtain somewhat greater extremes in soil-moisture content than ordinarily occur in the region in which these experiments were conducted, the soil over the root system of one tree was protected from rain for several weeks by means of waterproof tarpaulins, as has been noted. This shelter was erected on August 31, 1933, when the average soil-moisture percentage for the upper 12 inches in the experimental block was 18.1. It was removed on October 6, when the 12-inch index for the sheltered soil had decreased to 12.4 percent and that for the rest of the block was 17.4 percent. Immediately after the removal of the tarpaulins the soil area that had been covered was given a flood irrigation equivalent to 4 inches of rainfall. About 10 hours later the 0- to 12-inch soil-moisture content for this area was found to have increased to 20 percent. This sudden increase in soil moisture failed to produce any cracking. Similar irrigation of one tree in 1932, without previous use of tarpaulins but following prolonged dry weather, had also failed to produce cracking. A heavy straw mulch had no apparent influence on cracking, although such a soil cover retards water loss from the soil while it permits free penetration of rain water.

Between August 31 and October 6, 1933, there was cracking of the fruit on the tree with the tarpaulin-sheltered root system when cracking was common among other trees of the experimental block. Since the soil about the roots of this tree was protected from being wetted by rain throughout that period, it is clear that wetting of the soil was not required to produce cracking. Whether or not a sudden and sufficiently pronounced rise in soil-moisture content following a period of very dry soil may lead to cracking of apples under certain conditions is, of course, still an open question; but the present study furnishes no clear evidence that wetting of the soil was causally related to the cracking here recorded. Under the natural and the artificially modified soil conditions of this study, it appears that very slow atmospheric evaporation was probably the immediate external cause of cracking.

Fruits Protected from Wetting by Rain

With the possibility in mind that direct water absorption through the apple skin in a period of rain may sometimes be a contributing cause of cracking, the following experiment was carried out. A large

branch, bearing about 50 apples, was covered with a waterproof tarpaulin when rain occurred, the cover being removed when rain had ceased and the rest of the foliage was no longer wet. In a period of no atmometric evaporation, which was accompanied by rain, three of these protected apples cracked in spite of the fact that their skins were superficially dry. Although the number of apples involved in this test was not sufficient to furnish general evidence as to whether the prevention of wetting reduced the percentage of cracking, the result clearly supports the evidence already discussed that wetting of the fruit surface by rain is not, at least in general, necessary to cause cracking. The presence of rain water on the fruit may, however, favor cracking when other influences also are favorable to it.

Attached Branch Under Water

On September 30, 1932, a large Stayman Winesap branch bearing fruit without any cracks was bent down into a barrel of water so that all the apples and most of the leaves and small branches were submerged. This experiment continued for 4 days, and in that time severe cracking occurred. In the 4-day interval there were no periods of very low evaporation rates and no change of soil-moisture content other than the usual slow decrease due to ordinary evaporation and root absorption. At the same time no cracking of normally exposed fruits was observed, either on the same tree or on others. Measurements of maximal horizontal circumferences of the submerged apples, and of those on an adjacent untreated branch of the same tree, showed that in the 4-day period the mean rate of enlargement of the submerged fruits was much greater than that of the exposed ones. Details of this experiment are presented in table 1.

The fruits of both groups were originally of about the same size. The maximal enlargement percentage for submerged fruits (2.52) is almost double that for exposed fruits (1.34). The average enlargement percentages are 1.47 (submerged fruits) and 0.93 (exposed fruits), the former being about 1.58 times the latter; that is, the apples on the branch under water increased their maximal horizontal circumferences, on an average, about 58 percent more rapidly than did the apples on the exposed branch.

Twenty of the thirty-four submerged fruits cracked in the 4-day interval considered, but there was no cracking among the exposed fruits. The submerged fruits may be classified in three groups, according to their rates of enlargement, nos. 1 to 11 being considered as enlarging slowly, nos. 12 to 22 as enlarging at an intermediate rate, and nos. 23 to 34 as enlarging rapidly. The average length of cracks in the slowly enlarging group was 0.75 cm (2 out of 11 apples cracked), in the median group 6.0 cm (7 out of 11 apples cracked), and in the rapidly enlarging group 7.6 cm (11 out of 12 apples cracked).

TABLE 1.—*Enlargement rates of Stayman Winesap apples still attached to tree, some on branch submerged in water and others normally exposed on adjacent branch of same tree, together with records of cracking for submerged fruits, September 30 to October 4, 1932*

[No cracking of exposed fruits occurred. Data are arranged in ascending order of enlargement rates in each group]

Apple no.	On submerged branch			On adjacent branch	
	Sept. 30, original circumference	Oct. 4		Sept. 30, original circumference	Oct. 4, increase in circumference
		Increase in circumference	Total length of all cracks		
	Centimeters	*Percent*	*Centimeters*	*Centimeters*	*Percent*
1	22.95	0.22	(1)	22.95	0.65
2	22.05	.45	(1)	22.70	.60
3	24.05	.63	(1)	22.15	.68
4	22.95	.65	1.1	21.30	.70
5	22.70	.66	(1)	21.55	.70
6	19.65	.76	7.1	19.65	.76
7	23.40	.85	(1)	24.30	.82
8	23.10	.86	(1)	24.15	.83
9	22.30	.90	(1)	23.60	.84
10	22.10	.90	(1)	23.40	.85
11	22.75	.90	(1)	22.20	.90
12	24.35	1.23	11.8	21.70	.92
13	19.55	1.28	(1)	21.12	.94
14	23.10	1.30	(1)	20.50	.97
15	23.20	1.30	1.1	20.00	1.00
16	23.00	1.30	1.4	24.65	1.02
17	21.65	1.39	(1)	24.05	1.04
18	22.50	1.51	5.7	23.90	1.04
19	22.50	1.51	17.6	23.20	1.08
20	21.80	1.60	(1)	23.00	1.09
21	20.70	1.69	14.8	22.75	1.10
22	23.50	1.70	14.5	22.60	1.10
23	21.50	1.86	(1)	22.85	1.10
24	24.05	1.87	1.5	22.55	1.11
25	21.10	1.90	6.9	21.35	1.17
26	23.20	1.94	12.0	21.20	1.18
27	21.90	2.05	10.0	23.70	1.26
28	20.55	2.20	9.9	23.70	1.26
29	24.50	2.26	3.2	23.35	1.29
30	22.10	2.26	9.6	23.05	1.30
31	21.90	2.28	6.3	22.90	1.31
32	21.65	2.31	5.8	22.30	1.34
33	21.50	2.33	4.9		
34	23.85	2.52	21.5		
Average	22.40	1.47	4.9	22.57	.93

[1] No cracking.

While the water treatment seems, in general, to have increased the incidence of cracking, especially when it also increased the rate of fruit enlargement, the severity of cracking was apparently influenced by conditions not taken into quantitative account, presumably by variable internal characteristics of the fruits at the time of the experiment. The occurrence of cracking seems to be dependent not so much upon the rapid enlargement of the fruit as a whole as upon extra rapid enlargement of a restricted region of the tissues. The following chance observation made on September 16, 1933, may bear on this suggestion. In an apple with more than a third of its volume involved in a soft rot extending from the surface to the core and so advanced that the diseased portion was reduced to a mass of soft pulp, severe cracking had taken place on the uninfected part. This cracking must have been entirely independent of enlargement of the fruit as a whole.

Leaf Injury and Defoliation

In a large block of Stayman Winesap trees near Shenandoah Junction, about 3 miles east of the Kearneysville orchard, which was used for most of this study, the crop of 1933 showed very little cracking (less than 0.5 percent), while 40 percent of the same year's crop at the Kearneysville orchard was cracked. The trees of these two orchards were of the same age (14 years), both orchards were on the same type of soil, and weather conditions must have been virtually the same for both. The two orchards were noticeably different in that the Kearneysville trees had been partially defoliated or their foliage had been somewhat injured by spray materials, whereas the foliage in the other orchard was unusually dense and healthy. More of the fruits at Kearneysville were partially russeted, probably due largely to spray injury, and more of them were sunburned or highly colored, due to greater exposure to sunlight. All of these conditions, i. e., russeting, sunburn, and high coloration appear to be associated with increased cracking. Similar relationships between foliage conditions and cracking were seen among individual trees and branches in the experimental block at Kearneysville, where the highest percentages of cracking were associated with the highest percentages of leaf injury or with the sparsest foliage.

Figure 4, *A* and *B*, shows the general appearance of densely foliaged branches with little cracking as compared with sparsely foliaged branches with severe cracking. Data of a more quantitative nature bearing on this relation between foliage density and severity of cracking were secured by comparing three representative branches of about the same size but showing different degrees of cracking with respect to the total fresh weight of the leaves. One branch (*A*, at Shenandoah Junction) showed no cracking and the other two (nos. 2–22 and 4–9, at Kearneysville) showed, respectively, slight and severe cracking. The apples on all three of these branches were virtually free of russet and other visible skin injuries. Table 2 presents these data.

Table 2.—*Comparative data on number and diameter of fruit and fresh weight of leaves as related to the occurrence of cracking in apples*

Branch no.	Apples on branch	Average diameter of apples	Total fresh weight of leaves	Degree of cracking
	Number	*Inches*	*Grams*	
A	103	2.75	1,710	None.
2–22	72	2.25	1,518	Slight.
4–9	76	2.75	828	Severe.

Attached Apples Enclosed in Brown-Paper Bags

In the autumn of 1932 about 200 Stayman Winesap apples on three experimental trees were bagged and these were observed from time to time, observations being made, at the same times, on a similar number of comparable fruits, previously tagged, on these same trees. Cracking of the unbagged fruits severe enough to furnish a useful measure of the effects of bagging did not occur until the bagged apples had been enclosed for 3 to 4 weeks—time enough for pronounced morphological and physiological alterations to take place. Therefore the bagged

FIGURE 4.—*A*, Part of a Stayman Winesap tree with dense foliage and little cracking, near Shenandoah Junction; *B*, part of a Stayman Winesap tree with sparse foliage and severe cracking, near Kearneysville, W. Va.

apples probably differed markedly from the controls long before the latter showed much cracking. When about 30 to 50 percent of the controls had cracked, only about 2 to 6 percent of the protected apples had cracked. This is shown by records taken on October 20, presented in table 3.

TABLE 3.—*Cracking of bagged and unbagged Stayman Winesap apples*

Tree no.	Bagged apples			Unbagged apples	
	Apples	Days bagged	Cracked	Apples	Cracked
	Number	*Number*	*Percent*	*Number*	*Percent*
3-12	110	30	6.4	90	54.4
4-11	50	27	6.0	50	30.0
4-12	50	20	2.0	50	30.0

By harvest time the enclosed apples had developed the solid yellow ground color characteristic of this variety at full maturity, but they were devoid of any trace of red overcolor. It is reasonable to suppose that protection for many weeks from the direct rays of the sun might so influence either the osmotic values or the structural characteristics of the apple as to make it less inclined to crack. The effects may, therefore, have been due to prolonged shading, just as dense foliage seems to have reduced the tendency toward cracking.

OIL-EMULSION SPRAYS

In 1932 extensive tests were conducted with different concentrations, and with different times of application, of fish-oil and mineral-oil sprays, on the supposition that the oily films left on the fruits might retard or prevent absorption of water through the skin and so reduce cracking. No effects upon cracking were observed, however. When sprayed and unsprayed apples were subsequently tested under water it was found that the sprayed fruits although distinctly oily to the touch, absorbed water about as rapidly as did the untreated ones. Apparently the oil sprays used had failed to reduce the permeability of the skin to water.

FRUITS REMOVED FROM THE TREE AND SUBMERGED IN WATER

The evidence thus far presented leads to the conclusion that wetting of the soil by rain or irrigation was not a considerable influence in promoting cracking in the experimental orchard. The other possible influence of rain (i. e., the maintenance for a time of a more or less complete liquid water layer over the fruit and foliar surfaces) is not shown by figure 3 to have been influential in producing cracking; but when an attached branch bearing fruit and leaves was kept under water for 4 days this treatment was very effective in producing cracking, especially in fruits in which the water treatment accelerated enlargement. The experiment with the submerged branch was supplemented by some additional experiments with apples removed from the tree and kept under water.

After the cut end of the stem and the calyx opening had been sealed with paraffin each apple was weighed and all were placed in water, where they were held for 2 days. They were finally wiped and reweighed, the weight gain of each was computed, and the degree of cracking shown by each was recorded as the total length of all its cracks. Data from this experiment with mature apples removed from the trees are shown in table 4.

TABLE 4.—*Weight increase and cracking in mature Stayman Winesap apples kept under water for 2 days, Oct. 24 to 26, 1931*

[Apples are arranged in the ascending order of their weight gains]

Apple no.	Original weight	Gain in weight	Total length of all cracks	Apple no.	Original weight	Gain in weight	Total length of all cracks
	Grams	*Percent*	*Centimeters*		*Grams*	*Percent*	*Centimeters*
1	207	0	[1]	11	255	2.35	3.75
2	222	.90	[1]	12	286	2.45	[1]
3	195	1.03	[1]	13	244	2.46	4.25
4	243	1.24	[1]	14	219	2.74	14.75
5	158	1.26	2.75	15	166	3.01	4.50
6	241	1.66	4.25	16	195	3.08	4.25
7	172	1.75	1.00	17	246	3.25	11.25
8	172	1.75	1.75	18	237	3.38	[1]
9	198	2.02	2.25				
10	220	2.27	1.25	Average	215	2.32	3.11

[1] No cracking.

These results are, in general, similar to those shown by the orchard test with growing apples still attached to the tree when the branch bearing them was kept under water for 4 days (table 1). The water treatment of detached apples resulted in much cracking, and most of the badly cracked fruit showed relatively large gains in weight.

As in the orchard experiment on cracking of attached apples under water, it is clear that this 2-day water treatment of mature, detached fruits did produce cracking, that it was more apt to do so when the rate of enlargement was rapid than when it was slow, and that severity of the cracking produced generally was greater for those fruits that enlarged more rapidly. Since the cut end of the stem and the opening of the calyx region were sealed, it is evident that weight gain must have been due to water absorption through the skin. This observation furnished additional evidence that such direct absorption is to be expected whenever the apple skin is kept externally wet for a sufficient time. The apples that failed to crack also absorbed water, and one of these (no. 18) showed the most rapid absorption of all.

EXPERIMENTS ON VASCULAR PRESSURE AND CONDUCTION

A few experiments were performed with reference to possible relations between the occurrence of cracking and conditions that might influence the supply of water and other substances to the fruit. These are briefly described below.

Vascular Sap Pressure in Attached Branches

Mercury manometers were connected to small glass cylinders filled with water and fastened over the cut surfaces where tip portions of attached branches had been removed. These manometers invariably

showed maintained pressure deficits in the attached branches. It was thus apparent that the hydrostatic pressure of the vascular sap generally was considerably less than the gas pressure of the surrounding air. This was true even when cracking of the fruits was in progress, but the pressure deficit was smaller in periods of low evaporation rates than at drier times. Degrees of suction amounting to from 143 mm of a mercury column to 400 mm were observed. The method used is of course inadequate to show maximal pressure deficits, and it seems safe to suppose that the deficits recorded were generally smaller than the actual current deficits in uninjured trees or even in the cut branches some distance back of the cut surfaces. We may, in any event, conclude that vascular hydrostatic pressure in a branch when apples were cracking generally was considerably less than the current barometer reading.

These manometer experiments indicate clearly that there was no general vascular pressure excess in these trees, which might, as some writers seem to think, act to force water into the fruits at times of cracking. There was no evidence of positive excess pressure derived from the roots and transmitted throughout the tree, such as seems to have been postulated whenever the term "root pressure" has been employed in the elaboration of hypotheses concerning cracking of fruits and other phenomena connected with plant-water relations.

Excessive Water Pressure Artificially Produced in Branches

Some unsuccessful laboratory attempts were made to cause apples to crack by forcing water under excessive pressure into the cut basal ends of branches bearing fruit. The cut end of the branch, where the latter had been detached from the tree, was tightly sealed into the large opening of a tubulated filter flask containing water enough to cover the cut surface to a height of about 5 cm, and a Schrader valve, such as is used in automobile tires, was securely fastened to the tubulature by means of a bit of rubber tubing and a wire ligature. Then a hand-operated compression air pump was connected to the valve and air was pumped into the flask to increase the gas pressure in its upper portion and so force water into the branch. Pressures of from 5 to 10 pounds were employed. No cracking of the fruit resulted from this treatment, in which branch and fruit were exposed to the air of the laboratory. This experiment was not tried with branch and fruit surrounded by water-saturated air.

Within a few minutes after pressure had been applied to the system, water dripped rapidly from surfaces where ends of lateral twigs had been cut off, and more slowly from cut midribs of leaves; but no exudation appeared at surfaces where fruit stems had been cut. These tests lasted from 30 minutes to 3 hours. The results would be more significant if the artificially produced excessive vascular pressure had been applied for a longer time and if transpiration had been prevented, as by keeping leaf and fruit surfaces continuously wet.

Dye Solutions Absorbed Through Cut Ends of Branches Still Attached to Tree

Aqueous dye solutions were fed into the cut ends of small branches from 1 to 2 cm in diameter, and dye penetration into nearby fruits was observed. Both acid fuchsin and methyl blue were used with

equally satisfactory results. The solution entered under the influence of vascular-pressure deficit, no excess pressure being applied. The color contrast of either dye with the whitish flesh of the apple was quite striking, the dyed regions standing out clearly when the fruit was cut open. The dyes appeared in the regions of the vascular bundles and to a greater or lesser extent in contiguous meristematic tissues. Methyl blue was detected in very small veinlets close under the skin.

A striking feature of the penetration and accumulation of these dyes was their consistently greater concentration in regions subjacent to abnormal peripheral tissues, such as russeted areas, apple-scab lesions, and old cracks. Although sap movement through the vessels was probably somewhat more rapid and perhaps somewhat more extensive than was indicated by dye accumulation in the cell walls, yet there is no reason to suspect that the dye ever moved more rapidly than the sap that carried it, and the final presence of more dye in one region than in another surely means that sap had moved into the more intensely stained parts more rapidly than to other parts that showed less dye accumulation. It therefore appears that sap flow to the modified or injured peripheral regions just mentioned was much more rapid than to uninjured peripheral tissues, and this apparently indicates, in turn, that transpiration was more intense from the injured tissues than from other peripheral regions of the fruit. Baker (*1*) found that transpirational water loss through the corky tissue of russeted regions of apples was considerably greater than through normal epidermis and cuticle. Since the tissues just beneath the corky regions do not wither as long as the apples are on the tree, but remain turgid and healthy, this observation implies a more rapid movement of water into those regions.

From what has just been said it may be concluded that, except when transpiration is almost stopped, russeted, cracked, or otherwise locally injured peripheral tissues of the apple fruit transmit water from vessels to periphery more rapidly than do uninjured tissues, whose resistance to transpirational water loss is apparently greater; i. e., for the cells of the injured tissue both entrance of water and water loss generally are more rapid than for the cells of corresponding uninjured tissue. Many students have presented evidence in support of the general observation that larger bundles and more vessels develop in regions adjacent to rapidly transpiring surfaces than in other regions; in some unknown manner it appears that exceptionally rapid flow of sap through a developing bundle causes the formation of more vessels, or of more efficient ones, than would have been formed had the rate of sap flow been much slower. On the basis of this proposition it may be supposed that vascular resistance to sap movement is apt to be exceptionally low in those bundles that lead to the injured regions of the apple. If such is the case, vascular sap may be supposed to reach those regions with somewhat less hydrostatic pressure deficit than prevails in other regions, especially in times of very slow or negligible foliar transpiration, when vascular-pressure deficit must be exceptionally low throughout the whole tree. In periods of rapid transpiration the suction (or even liquid traction) arising therefrom should act to retard cell absorption everywhere. These considerations of logical possibilities may be assembled to furnish a hypothesis that

may explain, at least in part, why injured portions of apple periphery proved to be more susceptible to cracking than other portions, and why outbreaks of cracking and the occurrence of the most severe cracking were confined to periods when the general transpiration rate was unusually low.

INTERNAL CONDITIONS OF FRUIT IN RELATION TO CRACKING

General Relations Between External and Internal Influences

As has been pointed out, cracking of the fruit is of much more common occurrence in some apple varieties than in others. When cracking is prevalent in an orchard some trees usually are affected much more than others and some branches often are affected more than others on the same tree. Even on those fruiting branches exhibiting the most severe cracking when external conditions tend to promote this injury, some apples usually fail to crack. In the present study some apples were always found to be uninjured at harvest time, even on trees that exhibited high percentages of cracking.

It is therefore evident that cracking of individual fruits must be determined not alone by the occurrence of favorable weather conditions but also by some internal conditions effective within the fruit at times when the weather is favorable to cracking. The phenomenon of cracking is to be considered as the result of some combination or concatenation of circumstances, some of which may be traced almost directly to environmental fluctuations, while others appear to result from antecedent physiological processes of nutrition, growth, and development within the apple tree or within the fruit itself. In apples the formation of a crack shows that the fruit tissues involved, and perhaps other tissues also, were, when cracking occurred, unusually susceptible to the current cracking influence of the environmental complex, and it shows just as clearly that the conditions of the environment were such as to permit or facilitate crack formation in tissues exhibiting this particular kind and degree of susceptibility. Consequently the problem of the causation of cracking cannot be considered satisfactorily in terms of environmental conditions alone or in terms of internal conditions alone; both external and internal influences need to be taken into account.

The preceding sections of this paper deal mainly with cracking as it appeared to be related to environmental conditions, although attention is given to some internal conditions: e. g., vascular sap pressure and injured or modified regions of the fruit periphery. The present section deals with some observations on additional internal conditions: viz, abnormalities of peripheral tissues and the freezing-point depression of cortical tissues.

Abnormalities of Peripheral Tissues

As has been noted, cracking is less likely to occur on sound apples than on those with some abnormality of the peripheral tissues. Cracks are found much more often on portions of the fruit periphery that are marked by russeting, by scab lesions, or by sunburn than on other portions of the fruit. This point is illustrated by figure 1. Both in 1932 and 1933 the lesions that appeared earliest in any outbreak of cracking were predominantly on these modified parts of the

fruit surfaces. In 1933, 88 percent of the cracks formed on the fruits of one tree were directly associated with russeted skin, sunburn, or scab spots. The remaining 12 percent were in fruit surfaces that appeared otherwise to be perfectly healthy and unmodified. Cracks on otherwise sound fruits most often were on the cheek that was most exposed to sunlight. It should be emphasized, however, that cracking in apparently normal, uninjured peripheral regions has shown the same relationships to environmental fluctuations as was shown by cracking in the regions of modified periphery. Cracking in abnormal regions of the fruits as observed in these experiments is not to be regarded as a special form of the injury dependent on the abnormalities themselves, that is, the abnormalities merely render affected portions of fruits more susceptible to the injury than normal portions when environmental influences tend to promote cracking in both.

Freezing-Point Depression of Fruit Tissues

The observation that cracking was much more apt to occur on the most exposed side of an apple, especially when the skin and adjacent tissues on that side were modified by high coloration, sunburn, or russeting, leads to the suggestion that the turgor pressure in the tissues underlying the modified or injured portion of the periphery might be greater than that of corresponding tissues underlying unmodified peripheral regions of the same fruit. Brooks and Fisher (*3*) found that on very hot summer days the sunny side of an apple had a temperature from 10° to 16° F. higher than the shaded side. Juice expressed from the most exposed quarter of the fruit generally showed greater freezing-point depression than juice similarly expressed from the opposite quarter, and this difference was greater as the exposure of the first quarter was more pronounced. This was taken to indicate higher osmotic concentration in the cell sap of the tissues on the exposed side, which might be due, for example, to the higher temperature or to the more intense insolation on that side during periods of sunshine.

In a later paper (*4*) the same authors reported that exceptionally high osmotic values were indicated for tissue from the sunburned side, when one side was so injured; also that there seemed to be positive correlation between evaporation from a Livingston standardized white-sphere atmometer and the osmotic value of juice from apples in different parts of the tree, both being greatest in the position of greatest exposure to sunshine. A similar effect of seasonal conditions on the crop as a whole is suggested by Caldwell's (*6*) analyses of apple juice, which show, for many varieties, an unusually high sugar content in seasons with temperature and sunshine considerably above normal.

By means of the tissue-cup freezing-point method (*28*) many comparisons were made between sample cups from different regions of the same apple, especially between tissue samples from regions underlying unmodified skin areas and other tissue samples from regions underlying areas of high coloration, sunburn, or russeting. In some instances the more susceptible region of the apple tested had already cracked; that is, tissue underlying one or more newly developed cracks was compared, with reference to freezing-point depression, with tissue underlying an intact area of the same apple. After making the usual correction necessitated by supercooling, each freezing-point

depression was translated into terms of osmotic concentration in atmospheres by reference to the published table of Harris and Gortner (*15*). It should be emphasized that this index refers to the sample cup of tissue as a whole, not to its cell sap alone. It represents the capacity of the tested tissue to retain water against the influence of drying agencies, and it embraces not only the resilient pressure of stretched cell walls (which tends to squeeze water out of the cells), but also the osmotic value of the cell sap and of the liquid held in the walls themselves, as well as the imbibitional values of cell colloids and cell walls (which together act to retard water loss).

Results derived from 52 different apples of the Stayman Winesap variety, picked from eight different trees, are presented in table 5. Two values are shown for each apple, derived, respectively, from two tissue-cup samples taken from opposite sides of the fruit axis, with the longitudinal dimension of each cup parallel to the latter. The tissue of each cup was thus derived from a region opposite the middle portion of the apple core and about half-way between the core and the cheek periphery on that side. One of each pair of cup samples was taken from beneath a cheek area that showed modification of some sort, while the other sample was taken from beneath unmodified cheek periphery. Five kinds of visible modification or injury of peripheral tissue were recognized: (1) highly colored skin, uncracked; (2) sunburned skin, uncracked; (3) russeted periphery, recently cracked; (4) russeted periphery, uncracked; and (5) recently cracked periphery otherwise apparently unmodified.

It is seen at once that the tissue samples derived from beneath modified or cracked areas of the fruit periphery showed significantly higher osmotic values, in almost every test, than were shown by the samples derived from beneath unmodified areas. Since highly colored, sunburned, or russeted areas of the fruit surface have been found to be exceptionally prone to crack, this remarkable osmotic relation lends definite support to the supposition that cracking may result from excessive enlargement or excessive tissue pressure in localized subperipheral regions of the fruit cortex; for, other conditions being the same, regions of exceptionally high osmotic value should absorb water, and therefore enlarge, more rapidly than neighboring regions of lower osmotic value. The data of table 5 therefore indicate a reason why cracking is most likely to occur over regions of the cortex that are superficially marked by high coloration, sunburn, or russeting. The averages for the several sections of table 5 lead to the same conclusions as are reached from more detailed study. For every group of comparisons the average for the unmodified is smaller than for the modified areas.

TABLE 5.—*Osmotic values (in atmospheres) of tissue samples from opposite sides of the same apple (Stayman Winesap) computed from freezing-point depressions obtained in 1933 by means of the tissue-cup method (28)*

Tissue from beneath skin of high coloration, uncracked			Tissue from beneath sunburned periphery, uncracked			Tissue from beneath russeted periphery, recently cracked			Tissue from beneath russeted periphery, uncracked			Tissue from beneath recently cracked but otherwise unmodified periphery		
Date	Tissue beneath modified periphery	Tissue beneath apparently normal skin	Date	Tissue beneath modified periphery	Tissue beneath apparently normal skin	Date	Tissue beneath modified periphery	Tissue beneath apparently normal skin	Date	Tissue beneath modified periphery	Tissue beneath apparently normal skin	Date	Tissue beneath modified periphery	Tissue beneath apparently normal skin
Sept. 22	14.20	13.36	Oct. 13	26.55	18.40	Sept. 30	26.67	17.80	Sept. 22	19.48	13.84	Oct. 7	16.96	15.52
	22.60	13.96		23.44	17.92	Oct. 10	22.12	17.20		13.72	12.76		18.64	17.08
Sept. 29	18.52	20.80		24.75	19.48	Oct. 13	17.32	16.66		13.00	11.32		20.68	17.68
Sept. 30	18.40	17.32	Oct. 15	23.68	18.76		18.76	16.36	Sept. 25	24.52	16.48	Oct. 10	18.04	19.12
	25.95	16.24		25.59	17.80	Average	21.22	16.99		21.28	19.00		18.04	17.50
	21.52	17.20	Average	24.59	18.30				Sept. 30	22.48	17.68	Oct. 11	17.44	17.80
	19.00	16.00								18.76	18.76		19.24	18.16
Oct. 16	19.72	16.72							Oct. 4	19.72	17.08	Oct. 13	18.88	16.24
	19.12	15.76							Oct. 5	21.88	15.76		18.88	15.40
	19.12	16.00								18.40	16.36	Average	18.53	17.17
	20.08	17.56							Oct. 11	19.84	19.24			
Oct. 24	19.60	17.32								19.84	19.24			
	19.12	16.84								19.36	17.68			
	18.28	17.92							Oct. 15	22.12	20.32			
	20.20	19.24							Oct. 24	20.08	17.32			
Oct. 25	20.08	17.72												
	23.32	20.44							Average	19.63	16.86			
	22.25	22.84												
Average	20.06	17.51												

Pronounced localization of high tissue pressure is clearly indicated, and it seems likely that differences within the same apple might be found to be even greater than those shown in table 5 if it were possible to employ smaller tissue samples in freezing-point determinations of this kind. An attempt was made to chart the pressure variations somewhat more in detail through the use of 5 tissue cups from each apple instead of 2, the positions for sampling being symmetrically arranged around the fruit axis. The results of these more elaborate tests were in excellent agreement with those set forth in table 5. A representative set of data from five samples is shown in figure 5. The small circles represent the positions of the tissue cups studied, and the numerical values within these circles are osmotic values like those given in table 5. Apparently there was a tissue-pressure gradient in the subperipheral cortex of the fruit, between a high pressure underneath the more exposed peripheral area and a much lower pressure in the corresponding region on the opposite side of the fruit axis.

When the several local osmotic pressures found by employing 4 or 5 tissue samples from the same apple were averaged, to give an approximation of the mean-tissue pressure of the whole fruit, it was found that this mean value showed no relation to cracking. Some apples with low means were badly cracked while some with much higher means showed no cracking. It is therefore indicated that the internal conditions that favor or hinder cracking are not to be studied by means of freezing-point values derived from whole apples or from pulp or juice obtained by grinding or pressing the entire fruit.

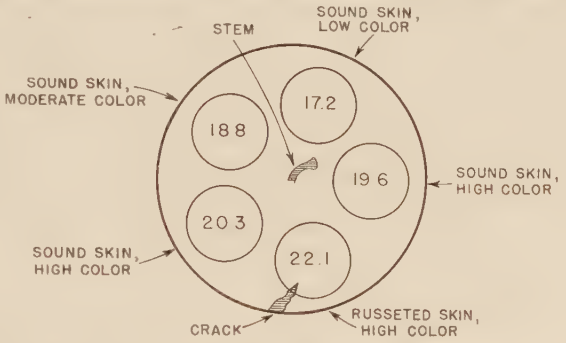

FIGURE 5.—Graphic representation of osmotic values, in atmospheres, of tissue samples from different portions of one Stayman Winesap apple.

There was apparently no relation between a tendency to crack and the absolute tissue pressure of the subperipheral cortex; cracking might be associated with a local tissue pressure of only 15 atmospheres in one apple, while a local pressure of 20 atmospheres or more might be found in another apple that was still sound. It seems that cracking must be related, in general, not to the local subperipheral pressure itself but to the magnitude and distribution of the pressure gradient just mentioned. In short, one of the main internal conditions leading to crack formation appears to be the occurrence of an excessive tissue pressure in a restricted area of the fruit cortex, accompanied by much lower pressures in neighboring regions.

SUMMARY AND CONCLUSIONS

This paper deals with cracking of the peripheral tissues of Stayman Winesap apples, which is considered in relation to current environmental and internal conditions. The discussions and views presented

are based on (1) observational studies carried out on cracking under natural conditions in an experimental orchard at Kearneysville, W. Va., (2) orchard experiments in which some environmental conditions were artificially modified, and (3) special laboratory studies.

Sudden, great increase in soil-moisture content has been suggested by some writers as a probable major factor contributing to cracking of fruits in general, but the observations and experiments recorded in the present paper fail to furnish any evidence in support of this hypothesis. Pronounced fluctuations in soil-moisture content, greater and more rapid than are ordinarily met with in orchards, showed no relationship to either the occurrence or the severity of cracking.

Under natural orchard conditions the occurrence of cracking was always found to be associated with very low rates of evaporation. Rainfall was naturally confined to periods so characterized, but cracking was clearly correlated with the slow evaporation rather than with the rainfall. Thus, extensive cracking occurred in several instances of prolonged slow evaporation rates when there had been no rainfall for from 36 hours to 6 days; and in other instances no cracking was observed after heavy rains when the accompanying low evaporation rates were of short duration. An outbreak of cracking was generally preceded by a period of 6 hours or more during which a standardized black porous porcelain atmometer sphere with automatic recorder showed no measurable water loss and the water-saturation deficit of the air was very low. This correlation may be taken to indicate that outbreaks of cracking were generally brought about by greatly depressed transpiration, maintained for 6 hours or more. During a period of very slow transpiration the water supply available to the fruits should be very abundant, permitting unusually rapid enlargement of fruit cortex if other conditions are favorable for tissue swelling. If, at the same time, rain water is being absorbed appreciably through the peripheries of fruits and leaves, swelling of the fruit cortex should be still further increased.

Mercury manometers connected to attached branches where the branch tips had been cut off showed vascular suction at all times, even while nearby fruits were in process of cracking. No evidence was found to favor the supposition that excessive vascular pressure (commonly referred to as "root pressure") was generally present throughout these apple trees at any time; atmospheric pressure apparently always exceeded the hydrostatic pressure within the vessels of the branches. Attempts to produce cracking artificially by forcing water, under 5 to 10 pounds of excessive pressure per square inch, into the cut ends of detached branches bearing fruit failed when branch and fruit were exposed to the air of the laboratory and the treatment was continued for 3 hours or less.

Since change in soil-moisture content did not noticeably influence cracking in this study it appears that precipitation was not influential through wetting of the soil. Rainfall may be influential in other ways, however, for when fruit and leaf surfaces are more or less thoroughly covered with water during periods of rain, considerable water absorption may occur through those surfaces, while transpiration is correspondingly retarded or prevented. When rain was artificially diverted from large branches some of the apples on those branches cracked, although they and the accompanying leaves were thus kept superficially dry, which seems to indicate that the presence

of a film of water on foliage or fruit, or both, was not a necessary condition to promote cracking. On the other hand, when a fruit-bearing branch, still attached to the tree, was kept under water for several days the submerged apples showed severe cracking; and cracking was also artificially induced when detached apples, with stems and calyxes sealed, were kept under water for several days, suggesting that long-continued wetting of fruit and foliar surfaces by rain might aggravate the tendency to crack when other conditions tend to promote this injury. There is no doubt that the apples of this study were able to absorb water at a considerable rate when their skins were kept superficially wet. Enclosing attached apples in paper bags to prevent wetting of the skins by rain greatly reduced cracking in the apples so treated after the bags had been in place for 3 or 4 weeks; in that time, however, the internal conditions of the bagged apples may have changed greatly.

The occurrence and severity of cracking were not shown to be related in any way to air-temperature fluctuation.

Not all the apples on a branch or tree cracked when the weather conditions were favorable to cracking, and it is evident that some fruits were, at any time, more susceptible to cracking than others. A period of little or no evaporation apparently induced cracking of the currently most susceptible fruits only. With the recurrence of low evaporation rates additional fruits cracked, suggesting that this susceptibility of individual apples was likely to increase throughout the season. Some fruits cracked early in the season while others still remained sound at harvest time. A study of certain internal conditions that may have influenced predisposition to crack led to several apparently significant observations, as follows:

In a great majority of observed cases of cracking the injury was initiated in a region characterized by some form of visible abnormality or modification of the peripheral tissues of the fruit: viz, russeting, scab lesions, sunscald, or unusually high coloration. Such modifications usually were found on the side of the fruit that had experienced the greatest exposure to sun, wind, and spray injury. In russeted areas many minute cracks appeared to have been progressively formed and then closed by cork tissues, leaving the fruit periphery more or less roughened and mechanically weak in such regions.

Apparently the immediate mechanical cause of cracking is a form of tissue strain by which the skin and the adjacent tissues in a restricted area of the apple are excessively stretched because of enlargement in deeper lying tissues beneath the same area. With weather conditions suitable for crack formation, it seems that rupture occurs in the most susceptible peripheral areas, where the subperipheral pressure exceeds the limit of extensibility of the outer tissues. Thus the formation of a crack is determined partly by the mechanical strength of the peripheral tissue and partly by the magnitude of the pressure exerted by the enlarging tissue beneath.

It was observed that, among trees and branches otherwise apparently comparable, cracking was more pronounced and extensive when the foliage was sparse than when it was dense. This difference may have been related to the greater incidence of sunscald, russeting, and intense coloration in the fruits of trees and branches with poor foliage.

When attached apples were kept under water, cracking generally occurred first and most severely in those individuals that showed the most rapid rates of enlargement, which suggests that rapid enlargement of the entire fruit may tend to produce cracking when other conditions are suitable. But some slowly enlarging fruits cracked while some rapidly enlarging ones remained sound, and it seems that the excessive tissue swelling that resulted in a crack was sometimes effective only beneath the immediate peripheral region where rupture was about to occur.

Freezing-point measurements of osmotic values within the apple tissues showed, almost without exception, that tissue samples from regions beneath modified areas of the fruit periphery had significantly higher pressures than had similar samples from unmodified areas. For example, an apple with a russeted area on one side showed a high osmotic value beneath that area and a much lower osmotic value beneath the corresponding area on the opposite side of the fruit, with a gradient between these two regions. It therefore appears that the russeted or otherwise modified region was characterized not only by mechanical weakness of the periphery but also by exceptionally high tissue pressure in the deeper lying cortex. Both of these characteristics would be expected to favor cracking.

When aqueous dye solutions were fed into the cut ends of attached branches bearing fruit, the solutions were absorbed into the branches and carried into nearby apples, where the dyes became most concentrated in those parts of the peripheral regions characterized by russeting, scab lesions, or previously formed and more or less suberized cracks. Movement of vascular sap into the tissue beneath these modified regions and the passage of water out of them by transpiration were more rapid than elsewhere. With a low evaporation rate and consequent slow transpiration, it appears that the cortex beneath modified periphery may receive water more freely than other parts of the same fruit. This may promote excessive swelling beneath the modified areas.

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U. S. GOVERNMENT PRINTING OFFICE: 1935

VITA

Leif Verner was born on May 15, 1900, at Oakmont, Pennsylvania, where he subsequently secured his grade school and high school education. After a period of service on the Mexican border as a private in the United States Cavalry in 1918-19, he entered the Pennsylvania State College, from which he received the Bachelor of Science degree in 1924 and the Master of Science degree in 1926. With the exception of spare time given to graduate study at the Pennsylvania State College, the years 1924-26 were devoted to teaching biology and general science in the high school at State College, Pennsylvania. As a Fellow of the American Scandinavian Foundation, appointed for a study of climatic influences in the distribution of cultivated fruit species on the Scandinavian Peninsula, he spent the academic year 1926-27 in part-time study at the University of Upsala, Sweden, and in travel in Sweden and Norway. Upon returning to the United States in the summer of 1927 he was appointed Assistant Professor of Horticulture at the University of Idaho, where he spent the next three years in teaching and research. In the summer of 1930 he went to the University of West Virginia where he served for one year as Assistant Professor of Horticulture, after which he was transferred by that institution to carry on research work in Horticulture at the University Experiment Farm near Kearneysville, West Virginia. He was granted leave of absence from this position during the academic year 1933-34, which he devoted to graduate study and research in the Laboratory of Plant Physiology of the Johns Hopkins University, where he held a University scholarship.